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Authors

Dutton, Spencer M.
Banks, David
Brunswick, Sam
et al.

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Spencer M. Dutton, David Banks, Sam Brunswick, William J. Fisk

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Natural Ventilation in California Offices: Estimated Health Effects and Economic Consequences

Spencer M Dutton, PhD **David Banks, PhD** *ASHRAE Member* **Sam Brunswick, M.S.** *Student Member ASHRAE* **William J. Fisk, M.S., PE** *Fellow ASHRAE*

ABSTRACT

This study examines the human health implications of natural ventilation in California office buildings. We modeled work-time indoor ozone and particle exposures using data from four case studies in naturally ventilated offices and published data from mechanically ventilated offices. We also modeled the amount of time that windows would be open in the naturally ventilated office and used the results to estimate the difference in pollutant exposures for occupants of naturally ventilated versus mechanically ventilated, air-conditioned offices. Applying published concentration-response equations, the incremental changes in health outcomes that resulted from the difference in ozone and particle exposures for occupants in the two types of offices were modeled. We also estimated the differences in sick building symptom prevalence rates based on prior studies in naturally ventilated and air-conditioned offices. First-order estimates were produced of the health-related costs and benefits of retrofitting 10 percent of California's office space to use natural ventilation. Findings included a reduction in sick building syndrome symptoms valued between $4.3 million and $11.5 million per year and annual health-related costs between $130 million and $207 million from increased exposure to ozone and particles. Our estimates have a high degree of uncertainty and exclude potentially significant health-related costs and benefits of both naturally ventilated and air-conditioned buildings. Nonetheless, these estimates indicate that health-related costs of natural ventilation are significant and warrant further study. Mitigation options that could limit the health and economic impacts of natural ventilation are discussed.

INTRODUCTION

Natural ventilation, if used appropriately, has the potential to provide both significant HVAC energy savings (Brager 2010), and to reduce the prevalence of sick building syndrome symptoms (Seppanen 2002). Sick building syndrome symptoms are 30 to 200 percent more frequent in air-conditioned buildings. Applying natural ventilation strategies in buildings is also expected to change occupants' exposures to outdoor air contaminants, including particulate matter (PM) and ozone, both of which pose significant health risks (Pope, et al 2002, Samet, et al 2000, Weschler 2006). Prior studies have found that the health outcomes that arise from exposure to these contaminants have significant economic costs (U.S. EPA 2011, Hall et al 2008).

In mechanically ventilated buildings, outdoor air passes through a particle filter before being delivered to the occupied

Author Spencer Dutton is a post doctoral researcher at the Lawrence Berkeley National Laboratory, in the Indoor Environment Group, Berkeley, California. David Banks is a engineering consultant at CPP Wind Engineering, Fort Collins, Colorado. Samuel Brunswick is a research associate at the Lawrence Berkeley National Laboratory. Bill Fisk is a senior scientist and leader of the Indoor Environment Group at the Lawrence Berkeley National.

space, but in naturally ventilated buildings, outdoor air enters the occupied either space directly through operable windows or via passive ventilation openings that often do not filter incoming air. In both types of buildings, PM and ozone are removed from the air to some extent by deposition on indoor surfaces. Several prior studies have quantified indoor, and coincident outdoor, concentrations of particles less than 2.5 microns in diameter (PM2.5) and ozone in conventional mechanically ventilated buildings (Wu 2012, Burton 2000, Weschler 2000). However, few prior studies have assessed indoor concentrations of PM or ozone in naturally ventilated offices and no identified prior studies have assessed the health impacts and costs associated with the changes in exposure to those contaminants. There are also no identified prior published studies quantifying of the costs and benefits associated with reduction in sick building syndrome symptoms in naturally ventilated buildings.

This study focuses on analyzing the health-related risks and benefits of retrofitting California offices to use natural ventilation. These costs and benefits are quantified both in terms of the number of cases of specific health outcomes and the monetary value to society. Quantifying the monetary value of these costs and benefits aids in weighing tradeoffs and analyzing the significance of a building's ventilation choices.

METHODOLOGY

We made first-order estimates of the difference in annual exposure to ozone and PM2.5 for office workers in naturally ventilated offices compared to workers in conventional air-conditioned (AC) offices with sealed windows and particle filtration. We estimated the difference in indoor exposures for occupants, using published data on indoor-outdoor ratios of contaminant concentrations in convnetial AC buildings, and data on indoor-outdoor ratios collected in field studies of naturally ventilated offices. Indoor contamiant concentrations were estimated using hourly weather data (NNDC 2012) and outdoor contaminant data (U.S. EPA 2012a), for a representative city in 15 of the 16 California climate zones, using equations 1 and 2.

$$C_{AC} = IO_{AC} \times C_O \quad (1)$$

$$C_{NV} = (IO_{NV\_WO} \times Z_{WO} + IO_{NV\_WC} \times Z_{WC}) \times C_O \quad (2)$$

Where C_{NV} and C_{AC} are the hourly average indoor contaminant concentrations, in the naturally ventilated building and reference air-conditioned building respectively. C_O is the outdoor hourly average contaminant concentration taken from the weather data, IO_{AC} is the ratio of indoor to outdoor concentrations of contaminants in mechanically ventilated buildings. The proportion of open windows in the building for any given hour (Z_{WO}), was estimated using a window-use-model (Haldi 2009) that predicts likely window use for given weather conditions. Z_{WC} is the fraction of windows closed, IO_{NV_WO} is the indoor-outdoor ratio when windows are open, and IO_{NV_wc} is the indoor-outdoor ratio when windows are closed. The values of the three model constants, IO_{AC}, IO_{NV_wc}, and IO_{NV_WO}, are specific to each contaminant type. Constants IO_{NV_wc} and IO_{NV_WO} were based on new case study data, and IO_{AC} values were based on published data. The hourly difference in indoor contaminant concentrations (ΔC) for the two scenarios was estimated using equation 3.

$$\Delta C = C_{NV} - C_{AC} \quad (3)$$

Hourly estimates of ΔC are them used to calculate annual differences in occupant exposure. Based on the predicted differences in annual contaminant exposures, we predicted the difference in the number of cases of several health outcomes. The relationship between incremental exposure and health outcomes was based on previously published concentration response (C-R) functions (U.S. EPA, 2012b). This model considered the California population working in offices (CA-SEDD, 2012) and the proportion of the year spent at work (Sekhar, et al. 2003, Zuraimi, et al. 2004). The population in each climate zone was calculated using data by city from the Department of Finance (CA -DOF 2012) and a list of cities by climate zone from Building Standards (2008). The health impacts were estimated for a hypothetical scenario of retrofitting 10% of California office space, which is currently mechanically ventilated, to use natural ventilation.

The unit cost of health outcomes were employed to translate health outcomes to costs. In general, the unit costs were "willingness-to-pay" values that account for health care costs, lost work, and pain and suffering from a range of sources collated by the U.S. EPA (2012b).

We then estimated the effects of natural ventilation versus air conditioning on the prevalence rates of sick building syndrome symptoms based on a review of data from 11 studies (Seppanen and Fisk 2002). Sick building symptom health care costs estimates were based on annual average of $206 per office worker after adjusting for medical cost inflation (U.S. EPA 2007). Costs benefits from decreased sick building symptoms in naturally-ventilated offices were compared to health-related costs from increased exposure to ozone and PM2.5.

Finally, the impact of two mitigations on exposure-related health costs were estimated for three climates zones representative of the range of climates in California. In the first mitigation, mechanical ventilation with air conditioning is substituted for natural ventilation on high-pollution days. In the second mitigation, windows are simply closed on high-pollution days, i.e., days with daily average outdoor ozone or PM2.5 concentration above the 90th percentile for that location. Both mitigation strategies assume that forecasts of daily average PM2.5 and ozone concentrations would be used to preemptively close windows to limit occupant exposures on high-pollution days.

RESULTS AND DISCUSSION

Our analysis projects significant increases in adverse health effects from occupant exposures to ozone and particles, if offices in California were to substitute natural ventilation for traditional mechanical ventilation and air conditioning. Figure 1 and Figure 2 give the total number of cases for a range of health outcomes for 15 Title-24 climate zones based on the 500,000 office workers who would be affected if 10 percent of California offices were retrofitted to natural ventilation. Results are provided for scenarios A and B which use different sets of model inputs to bound the estimates given the range of reasonable model inputs, Error bars indicate the uncertainty in the total number of cases for each health outcome based only on the uncertainty in the three coefficients used in each of the C-R functions.

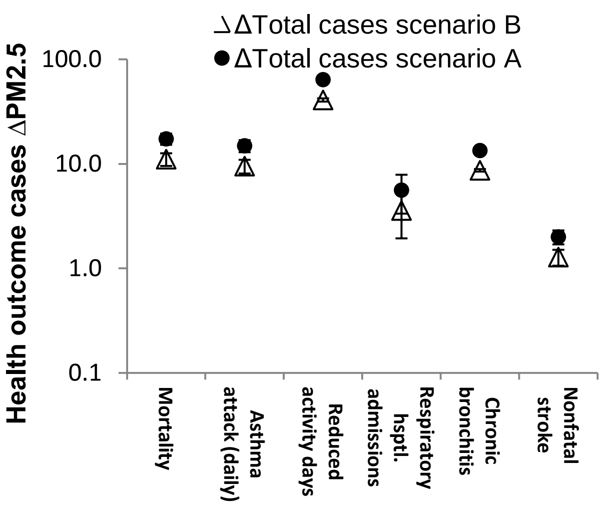

Figure 1. Total CA cases of health outcomes related to ΔPM 2.5 exposure

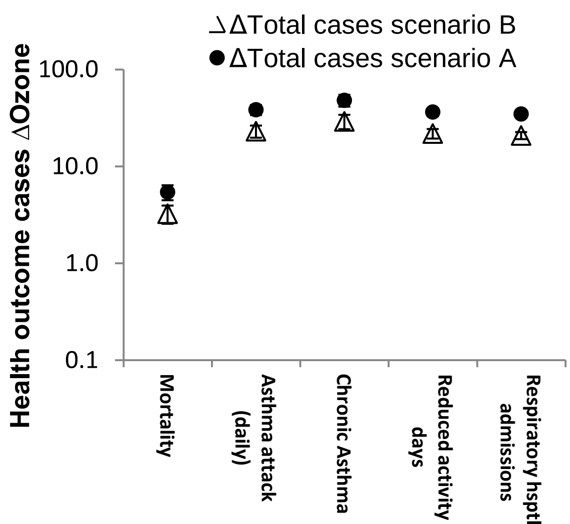

Figure 2. Total CA cases of health outcomes related to Δozone exposure

The central estimate of the number of cases of each health outcome was translated into an associated annual monetary cost, shown in Figures 4 and 5 using. The error bars shown in Figures 4 and 5 represent only the uncertainly in the monetary value of each health outcome, based on a single standard deviation.

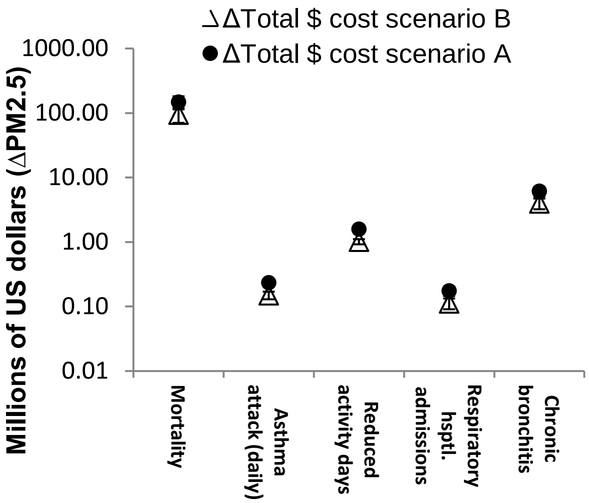

Figure 3. Total annual costs of health outcomes related to ΔPM 2.5 exposure

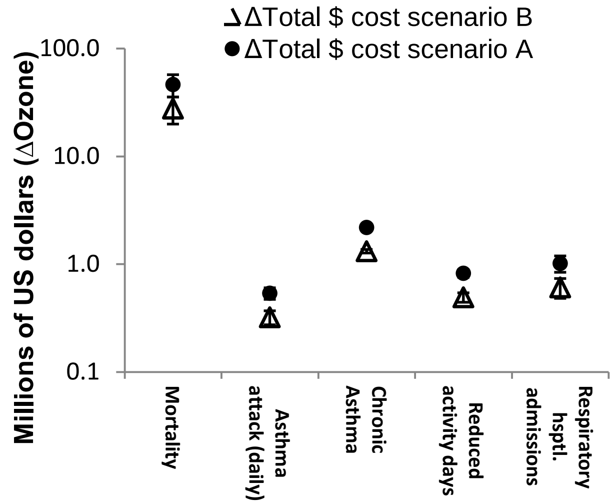

Figure 4. Total annual costs of health outcomes related to Δozone exposure

The analysis also projects coincident reductions in occupants' sick building syndrome symptoms. However, the costs of increased ozone and PM-related health effects outweigh the benefits from reduced sick building syndrome symptoms. If 10 percent of California's office buildings were retrofitted to use natural ventilation, the estimated net annual health-related cost is $130 to $207 million. Although these costs appear high, the projected number of workers who experience adverse health effects is small. Roughly 14 to 23 premature deaths are projected annually per 500,000 workers in the retrofitted buildings. At the same time, for every 500,000 workers in retrofitted buildings, a projected 22,000 to 56,000 fewer workers experience weekly sick building syndrome symptoms, which have a much lower monetary value than the more serious health outcomes from exposure to ozone and particles..

There are many substantial sources of uncertainty in the projections in this study, including: indoor/outdoor concentration ratios of ozone and particles (particularly for naturally ventilated offices), occupant window use, C-R functions and unit costs for health effects. In addition this study did not consider potential second order effects related to the energy savings associated with natural ventilation, these include potentially lower outdoor particle concentrations and global warming mitigation. Consequently, the estimates in this paper should be considered order-of-magnitude estimates.

Analysis of the two potential mitigation strategies that restrict window use on high-pollution days indicates that health effects and associated costs from exposure to outdoor air ozone and particulate matter could be significantly reduced. Incremental health related costs related to increased ozone exposure were on average 22% lower when applying mitigation strategy 1, and 19% lower for strategy 2. PM 2.5 related incremental costs were reduced on average 17% and 32%, for strategy 1 and 2 respectively. For both strategies, practical considerations would need to be addressed. One significant consideration is that restricted window use, because elevated ozone levels are likely to coincide with periods of hot weather; may cause occupants to be thermally uncomfortable unless alternative cooling was provided. We would also expect an increase in SBS symptoms and associated costs during periods when windows are closed. Other mitigation strategies might include installing particle filtration and ozone removal systems inside naturally ventilated buildings, including activated carbon mats. Further study is needed to determine the costs and performance of these mitigation options.

CONCLUSIONS

Retrofits that increase the use of natural ventilation in California's office buildings are projected to increase several adverse health effects as a result of increased indoor exposures to ozone and particles from outdoor air. Although the number of workers affected would be small if 10 percent of California offices were retrofitted, the high costs assigned to the resulting adverse health effects result in projected annual costs of one to two hundred millions of dollars per year for each 10 percent of California's office buildings converted from traditional mechanical ventilation with air conditioning to natural ventilation. Efforts are currently underway to quantify the energy cost savings associated with natural ventilation retrofits.

The same retrofits are projected to reduce the number of workers experiencing weekly sick building syndrome symptoms. For each 10 percent of California's office buildings converted to natural ventilation from traditional mechanical ventilation with air conditioning, a projected 22,000 to 56,000 fewer workers experience weekly sick building syndrome symptoms. However, the estimated health care cost savings from reduced sick building syndrome symptoms are overshadowed by the health-related costs from increased exposures to ozone and particles

The health effects and costs from increased exposures to ozone and particulate matter in naturally ventilated buildings could be substantially reduced by keeping windows closed on the days with the 10-percent highest levels of ozone and particulate matter, respectively. Mechanical cooling would likely be needed to maintain comfort, and mechanical ventilation would be needed to prevent an increase in sick building syndrome symptoms.

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